

The massive star binary fraction in young open clusters – I. NGC 6231 revisited

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ABSTRACT

We present the results of a long-term high-resolution spectroscopy campaign on the O-type stars in NGC 6231. We revise the spectral classification and multiplicity of these objects and we constrain the fundamental properties of the O-star population. Almost three quarters of the O-type stars in the cluster are members of a binary system. The minimum binary fraction is 0.63, with half the O-type binaries having an orbital period of the order of a few days. The eccentricities of all the short-period binaries are revised downward, and henceforth match a normal period–eccentricity distribution. The mass ratio distribution shows a large preference for O + OB binaries, ruling out the possibility that, in NGC 6231, the companion of an O-type star is randomly drawn from a standard initial mass function. Obtained from a complete and homogeneous population of O-type stars, our conclusions provide interesting observational constraints to be confronted with the formation and early evolution theories of O-stars.

Key words: binaries: close – binaries: general – binaries: spectroscopic – stars: early-type – open clusters and associations: individual: NGC 6231 – open clusters and associations: individual: Sco OB1.

1 INTRODUCTION

Although massive O-type stars are often so bright that they can be studied with small telescopes up to distances of a few kpc, our understanding of these objects is still fragmentary. Even their physical properties remain often ill constrained. The latter however provide key observational guidelines to solve one of the most critical astrophysical questions at present: how do massive stars form? In this context, we have undertaken a long-term monitoring of the O-type star population in a number of young open clusters in order to accurately derive and/or confirm their physical and orbital properties. This should help to clarify whether, as suggested by some authors (e.g. Penny et al. 1993; García & Mermilliod 2001), a correlation exists between the properties of a cluster and those of its member massive star population. The series of papers initiated here will focus on one of the fundamental properties of these objects, their multiplicity, although other properties of the population will be discussed whenever allowed by the data set. The present paper deals with a supposedly well known cluster, NGC 6231. Yet, the obtained picture is significantly different from the one proposed in earlier works, both in terms of the properties of the individual objects and those of the O-star population as a whole.

Located in the core of the Sco OB1 association, at about 1.64 kpc ($DM = 11.07 \pm 0.04$, Sana et al. 2006b), NGC 6231 is one of the rich nearby clusters in terms of number of hosted O-type stars (García & Mermilliod 2001, hereafter GM01). Sana et al. (2006b, 2007b) identified several hundreds of pre-main-sequence (PMS) stars, from which they derived a cluster age of 2–4 Myr, compatible with the evolutionary status of the massive stars in the cluster, and in good agreement with previous studies (Sung, Bessell & Lee 1998; Baume, Vázquez & Feinstein 1999). Using the X-ray properties of these PMS stars to disentangle the cluster low-mass members from the numerous field stars along the line of sight, they showed that the geometric centre of the cluster is located about 30 arcsec east of the massive binary HD 152248 (Fig. 1). Using a king profile fit, they further constrained the cluster core radius at about $d_c = 3.1$ arcmin which, at the distance of the cluster, corresponds to 1.5 pc.

Within 15 arcmin ($\equiv 7.1$ pc) around the cluster centre (about five times the core radius), one encounters over 90 B-type stars, 15 O-type stars and a Wolf–Rayet (WR) system (for a complete census, see Sana et al. 2006c). The spectroscopic binary (SB) fraction of these objects has already been investigated by several authors. Levato & Morrell (1983, hereafter LM83) derived a minimum fraction of binaries among main-sequence early-B/late-O stars $f_{\min} \sim 0.41$, from which the authors estimated a binary fraction $f \sim 0.57$. Raboud (1996) obtained a minimum fraction $f_{\min} \sim 0.52$ for the B-type stars. More recently, GM01 proposed an even larger fraction of 0.79 for the O-type stars, making NGC 6231 the second cluster in their sample,

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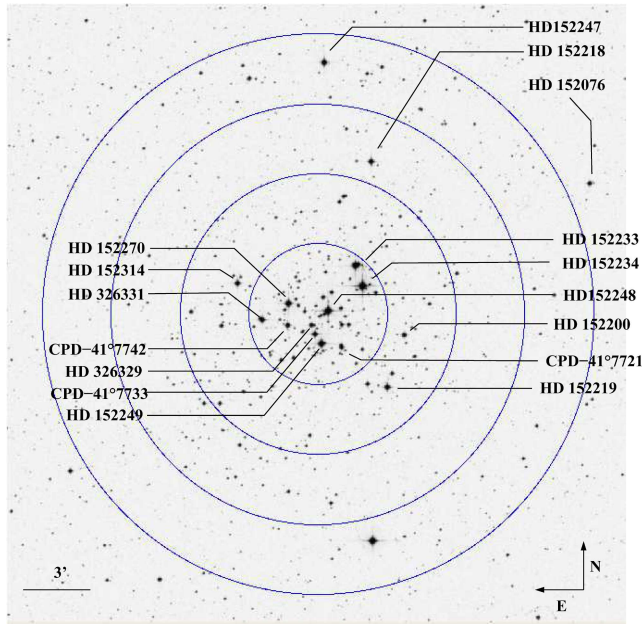


Figure 1. O/WR-type objects in NGC 6231. The circles are centred on the geometric centre of the cluster and have a respective radius of one, two, three and four times the cluster core radius $d_c = 3.1$ arcmin $\equiv 1.5$ pc.

after IC 1805 ($f \sim 0.80$), to have an O-star binary fraction close to 80 per cent. In line with the quoted studies, we adopt here the SB fraction (f) to be equal to the ratio of the number of binary or multiple systems to the total number of objects in the considered population. Beyond the SB fraction f , the fraction of companions per massive star, as defined by Preibisch, Weigelt & Zinnecker (2001), will also be briefly discussed in Section 4.5.

In the present paper, based on more than 150 high signal-to-noise ratio (S/N) high-resolution spectra, we revisited the current knowledge of all the O-type stars in NGC 6231. Our work is organized as follows. The observing campaign is briefly described in Section 2. The individual objects are discussed in Section 3 while Section 4 summarizes the properties of the O-type star population seen as a whole. It also discusses the implications in terms of constraints on the star formation process and on the cluster structure. Finally, Section 5 briefly summarizes our results.

2 OBSERVATIONS AND DATA HANDLING

Our team started to collect data on the O-type stars in NGC 6231 about 10 yr ago, focusing in the first few years on the brightest objects before later extending our survey to fainter targets in the cluster. Except for a few spectra obtained with the coude echelle spectrograph (CES) at the ESO Coudé Auxiliary Telescope (CAT, La Silla) in 1998, and with the bench-mounted echelle spectrograph (BME) attached to the CTIO 1.5-m Ritchey–Chrétien Telescope at Cerro Tololo, most of the present data set was acquired between 1999 May and 2004 May with FEROS (Fibre-fed Extended Range Optical Spectrograph) successively mounted at the ESO 1.5-m and ESO/MPG 2.2-m telescopes at La Silla. The data reduction techniques applied are identical to those used in previously published analyses of the bright short-period binaries in the cluster. We refer to our previous works on these objects for a complete description of the instrumental set-ups and of the data reduction (see e.g. Sana, Rauw & Gosset 2001; Sana et al. 2003; Sana, Rauw & Gosset 2007a). For each spectrum, Doppler shifts and equivalent widths (EWs) of a series of lines (Table 1) were measured by fitting Gaussian profiles to the spectral lines. For this purpose, we adopted the effective rest wavelengths from Conti, Leep & Lorre (1977) below 4800 Å and from Underhill (1994) above that limit. The spectral properties of the O-type stars were re-derived using the quantitative criteria of Conti & Alschuler (1971), Conti (1973), Mathys (1988) and Mathys (1989), that rely on the EW ratio of diagnostic lines. We adopt the usual notations: $\log W' = \log W(\lambda 4471) - \log W(\lambda 4542)$, $\log W'' = \log W(\lambda 4089) - \log W(\lambda 4144)$ and $\log W''' = \log W(\lambda 4388) + \log W(\lambda 4686)$. With respect to the latter criterion, based on the product of the EWs (expressed in mÅ), we emphasize that the star has to be single, or that the brightness ratio of the two components has to be known for this criterion to be applicable. Measured values are reported in Table 2. Whenever possible, B-type companions were also classified by comparing the measured EWs with the typical EWs, quoted by Didelon (1982), for a given spectral type.

Table 3 summarizes the derived radial velocities (RVs) and provides, object by object, the journal of the observations of all the O-type stars, with the exception of the five short-period binaries, which have been the subject of dedicated papers, and of the WR system. References for the latter objects are given in Table 4. Tables 1 and 3 show that, for most objects, we are able to investigate variability on time-scales of several hours to several years.

To further study the possible long-term variability, we also compared our measurements with results from earlier works. In the past,

Table 1. Number of RV measurements obtained for each object with respect to the considered spectral lines. ‘–’ means that the corresponding line has not been measured.

Object	He I λ 4026	Si IV λ 4089	He I λ 4144	He I λ 4388	He I λ 4471	Mg II λ 4481	He II λ 4542	He II λ 4686	He I λ 4921	He I λ 5876	He I λ 7065
HD 152076	–	1	1	1	1	1	1	1	1	1	1
HD 152200	–	16	16	16	16	–	14	16	–	16	16
HD 152233	–	–	31	31	34	–	34	–	34	31	31
HD 152234	28	28	28	28	28	28	28	28	28	28	23
HD 152247	16	16	16	16	16	–	16	16	16	16	16
HD 152249	32	34	33	34	34	–	34	34	–	29	29
HD 152314	16	16	16	–	16	–	16	16	16	16	16
HD 326329	–	–	8	8	10	–	8	8	8	8	8
HD 326331	–	–	–	–	13	–	13	–	–	13	–
CPD –41°7721	–	1	1	1	1	–	1	1	–	–	–

Table 2. Diagnostic line ratios and adopted spectral classifications for the studied O-type objects. Inappropriate criteria for specific cases are marked as ‘n/a’.

Object	$\log W'$	$\log W''$	$\log W'''$	Spectral type
HD 152076	0.52	0.08 – 0.09	5.3	O9.5 III
HD 152200	0.689 ± 0.048	0.162 ± 0.030	5.438 ± 0.022	O9.7 V
HD 152233 prim	-0.337 ± 0.024	n/a	n/a	O5.5 III(f)
HD 152233 sec	0.060 ± 0.076	n/a	n/a	O7.5 III/V?
HD 152234 prim	0.815 ± 0.028	0.341 ± 0.054	n/a	O9.7 I
HD 152234 sec	~ 0.17	≤ 0.0	n/a	O8 V
HD 152247 prim	~ 0.3	~ 0.28	n/a	O9 III
HD 152247 sec	> 0.7	< 0.0	n/a	O9.7 V
HD 152249	0.39 ± 0.02	0.554 ± 0.004	4.73 ± 0.06	O9 Ib ((f))
HD 152314 prim	0.265 ± 0.011	~ 0.27	n/a	O8.5 V
HD 152314 sec	n/a	n/a	n/a	B1-3?
HD 326329	0.49 ± 0.04	0.03 ± 0.03	5.43 ± 0.02	O9.5 V
HD 326331	0.14 ± 0.04	0.53 ± 0.10	n/a	O8 III((f))
CPD $-41^\circ 7721$	~ 0.41	-0.14 to -0.23	~ 5.5	O9 V

Table 3. Sample of the journal of the spectroscopic observations of the NGC 6231 O-type stars studied in the present paper. The two header lines indicate the considered spectral lines and the adopted rest wavelength (in Å). The first column gives the Heliocentric Julian Date at mid-exposure. The following columns provide the heliocentric RVs (expressed in km s^{-1}) using various spectral lines. The last two columns provide the mean and 1σ dispersion computed, for a given date, over the quoted lines. Whenever appropriate, the mean and 1σ dispersion for individual lines are also given at the bottom of each subtable. References for the instrumental set-up can be found at the bottom of the table. The full table is available in the electronic edition of the journal (see the Supplementary Material section).

HJD	Si IV λ 4089	He I λ 4144	He I λ 4388	He I λ 4471	He II λ 4542	He II λ 4686	He I λ 4921	He I λ 5876	He I λ 7065	Mean	Sigma
$-2\,400\,000$	4088.863	4143.759	4387.928	4471.512	4541.590	4685.682	4921.929	5875.620	7065.190		
HD 152200											
51669.900 ^a	−10.9	3.1	6.9	−33.3	1.9	−6.5		−6.5	−5.0	−6.3	12.4
52335.863 ^a	−31.8	−19.2	−16.1	−58.0	−29.7	−32.3		−21.8	−33.0	−30.2	13.0
52336.836 ^a	1.8	4.3	6.8	−35.9	6.3	−8.9		−1.3	−7.9	−4.4	14.1
52337.836 ^a	−10.3	−0.9	6.6	−30.5	4.8	−8.5		1.5	−7.4	−5.6	11.9
52338.818 ^a	−38.4	−22.7	−17.4	−57.4	−21.3	−36.9		−26.1	−36.9	−32.1	13.0
52339.806 ^a	−43.3	−30.5	−25.0	−63.5	−24.2	−42.2		−39.4	−37.9	−38.3	12.6
52383.836 ^a	−46.3	−33.8	−32.1	−69.9	−14.8	−36.3		−38.2	−40.4	−39.0	15.5
52782.744 ^b	−20.9	−10.8	−5.3	−40.6	−	−24.5		−13.8	−18.0	−19.1	11.4
52783.717 ^b	−46.1	−35.2	−26.1	−63.6	−	−44.7		−36.1	−38.2	−41.4	11.8
52784.715 ^b	−42.4	−28.3	−22.2	−62.5	−22.7	−35.2		−30.8	−39.4	−35.4	13.1
53130.741 ^b	−58.3	−47.7	−43.2	−79.5	−41.2	−58.1		−50.5	−57.0	−54.4	12.1
53131.778 ^b	−48.6	−28.1	−24.2	−63.8	−26.1	−45.8		−33.9	−33.6	−38.0	13.7
53132.645 ^b	−21.4	−11.6	−5.8	−43.6	−4.1	−21.6		−17.7	−17.5	−17.9	12.3
53133.715 ^b	−26.4	−12.0	−8.2	−45.2	−5.5	−26.4		−15.9	−20.8	−20.1	12.8
53134.827 ^b	−55.0	−42.0	−35.4	−74.4	−35.1	−55.3		−45.0	−47.9	−48.8	12.9
53135.676 ^b	−54.7	−43.6	−39.3	−77.5	−35.1	−59.1		−50.0	−52.8	−51.5	13.2
Mean	−34.6	−22.4	−17.5	−56.2	−17.6	−33.9		−26.6	−30.9	−30.2	12.9
Sigma	18.1	16.5	16.3	16.0	15.8	17.0		16.6	16.3	16.3	1.0
HD 326329 \equiv CPD $-41^\circ 7735$											
50995.687 ^c	−	−	−38.7	−	−	−	−	−	−	−	−
50996.617 ^c	−	−	−36.7	−	−	−	−	−	−	−	−
51671.911 ^a	−20.0	−18.3	−19.6	−38.1	−21.5	−24.7	−18.1	−14.6	−21.86	7.2	
51672.901 ^a	−14.9	−17.5	−26.2	−33.5	−21.9	−19.9	−14.5	−13.7	−20.26	6.8	
53130.709 ^a	−15.9	−20.5	−28.2	−22.0	−18.1	−22.2	−17.8	−14.9	−19.95	4.3	
53131.747 ^a	−15.0	−20.6	−28.6	−22.7	−18.6	−23.5	−16.8	−15.6	−20.18	4.6	
53132.781 ^a	−18.0	−21.6	−31.4	−27.7	−21.6	−25.2	−20.7	−19.3	−23.19	4.6	
53133.816 ^a	−16.8	−20.9	−26.7	−22.7	−20.3	−23.3	−17.6	−19.5	−20.98	3.2	
53134.691 ^a	−17.7	−20.8	−29.5	−23.6	−18.0	−24.7	−19.0	−18.1	−21.43	4.2	
53135.735 ^a	−18.1	−21.8	−29.9	−23.4	−23.2	−23.9	−19.5	−16.6	−22.05	4.1	
Mean	−17.1	−20.3	−29.6	−26.7	−20.4	−23.4	−18.0	−16.5	−21.2	4.9	
Sigma	1.7	1.5	5.4	6.0	2.0	1.7	1.9	2.2	1.1	1.4	

^aESO 1.5 m + FEROS; ^bESO/MPG 2.2 m + FEROS; ^cCAT + CES; ^dCTIO 1.5 m + BME.

Table 4. Selected orbital and physical parameters of the short-period binaries in NGC 6231.

Object	P (d)	e	m_1/m_2	Spectral type	Reference
CPD $-41^\circ 7742$	2.440 70	$0.027^a \pm 0.006$	1.803 ± 0.015	O9 V + B1.5 V	Sana et al. (2003)
HD 152219	4.240 32	0.082 ± 0.011	2.530 ± 0.023	O9 III + B1-2 V/III	Sana, Gosset & Rauw (2006a)
HD 152248 ^b	4.816 02	0.133 ± 0.005	1.012 ± 0.011	O7 III (f) + O7.5 III (f)	Sana et al. (2001)
HD 152218	5.603 91	0.259 ± 0.006	1.319 ± 0.014	O9 IV + O9.7 V	Sana et al. (2008)
CPD $-41^\circ 7733$	5.681 504	0.0 (fixed)	2.640 ± 0.012	O8.5 V + B3	Sana et al. (2007a)
WR 79 (HD 152270)	8.8911	0.0 (fixed)	2.7	WC7 + O6V	Luehrs (1997), Hill et al. (2000)

^aWe note that Bouzid, Sterken & Pribulla (2005) reported a circular orbit for CPD $-41^\circ 7742$.

^bThe orbit has been recomputed using the new version of the Liège orbital solution package (Sana et al. 2006a) for a better handling of the errors.

RV measurements on cluster stars have mainly been performed by Struve (1944), Hill, Crawford & Barnes (1974, hereafter HCB74), LM83, Perry et al. (1990, hereafter PHYB90) and GM01. Note however that these authors report (mean) RVs based on different lines, so that direct comparison of the quoted RVs from one author to the other, or with the current work, should be considered as indicative only. The most recently published photometric studies are from Perry, Hill & Christodoulou (1991, hereafter PHC91), Balona & Laney (1995, hereafter BL95), Raboud, Cramer & Bernasconi (1997, hereafter RCB97), Sung et al. (1998, hereafter SBL98) and Baume et al. (1999, hereafter BVF99). Sung (private communication) also obtained $UBV(RI)_C$ photometry over a 40×40 -arcmin² field of view down to $V \sim 23$ (for a brief description of the data, see Sana et al. 2006b).

Investigating the multiplicity of massive stars is a difficult task, not only because of the numerous observational biases, but also because of the large parameter space that must be searched. In the present approach, we adopt either of the following two criteria as a definite proof that an object is a binary system: (i) the presence of Keplerian (and periodic) RV variations or (ii) the detection of a composite (SB2) and variable spectrum.

In the first case, we are able to compute an orbital solution, thus constraining most of the orbital parameters. In the second case, the detection of the secondary spectrum also provides valuable information. Indeed, the spectral types of both components offer a reasonable estimate of the mass ratio and the detected RV variations yield a first, albeit rough, idea of the time-scale of the orbital period.

As described below, some objects in our sample show RV variations that we have not been able to link with a Keplerian motion, nor have we been able to detect the secondary signature. While some of these objects are potential binary candidates, their multiplicity nevertheless awaits more definite confirmation. Combined with the fact that we are actually observing the entire massive star population in the cluster and not a subsample of it, the present approach offers the advantage of providing a firm lower limit on the binary fraction in NGC 6231, which is unaffected by statistical errors.

3 THE O-TYPE STAR POPULATION IN NGC 6231

As mentioned earlier, 15 O-type objects are found within 5 core radii from the cluster centre (Fig. 1). In the present section, we revisit the properties of each of these objects individually.

3.1 Short-period binaries

Detailed analyses of the five short-period binaries were presented in a series of papers since 2001. Table 4 summarizes the main physical and orbital properties of these objects. We note that they significantly differ from the results quoted in the contemporaneous work

of GM01. Implications for the general properties of the NGC 6231 O-star population, as well as constraints on our understanding of the formation and dynamical evolution of these objects, will be discussed in Section 4.

3.2 Long-period binaries

3.2.1 HD 152234

HD 152234 is reported in the literature as a B0Iab RV variable star (Levato & Malaroda 1980). Levato et al. (1988) proposed a very preliminary period of 27.25 d, while GM01 claimed to have found the companion signature and derived a period twice as long ($P = 54.6$ d). Their computed orbital solution is slightly eccentric ($e = 0.183 \pm 0.093$) and they estimated $K_1 = 46.5 \pm 2.8$ km s⁻¹ and $K_2 = 211.5 \pm 6.1$ km s⁻¹ (rms = 13.5 km s⁻¹).

Between 1999 and 2004, we have obtained 23 FEROS spectra and five BME spectra. From our observations, HD 152234 most probably consists of an O9.7 supergiant primary and an O8 main-sequence secondary. The secondary signature is faint (Fig. 2) and is only seen at very few phases. This partly results from the lower S/N of some of the spectra in our data set. Our current data definitely rule out the period of 54.6 d proposed by GM01 and point towards a preliminary value close to 126 d (Fig. 3). Although the orbital

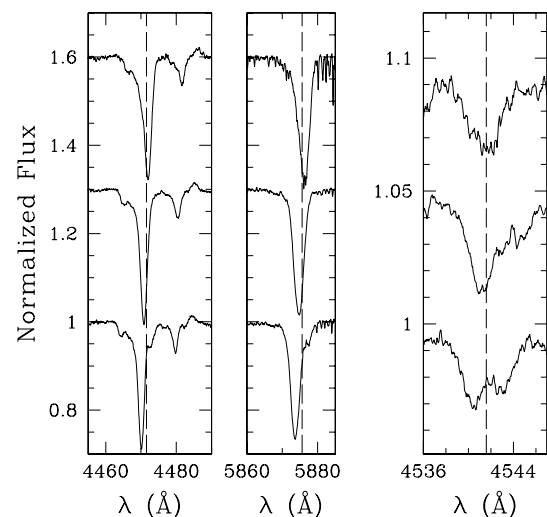


Figure 2. HD 152234: He I $\lambda\lambda$ 4471, 5876 (left-hand side) and He II λ 4542 (right-hand side) line profiles at three different epochs. The orbital shift of the primary is clearly seen. The secondary component is clearly visible, blueshifted, in the top spectrum and redshifted in the bottom one. Vertical dashed lines indicate the adopted rest wavelengths.

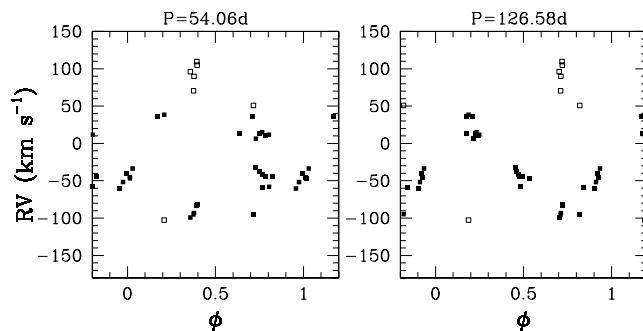


Figure 3. HD 152234: He I λ 4471 RVs folded against two values of the orbital period. Filled (respectively open) symbols indicate primary (respectively secondary) RVs.

properties await further constraints, we nevertheless confirm that HD 152234 is a long-period O-type binary.

3.2.2 HD 152233

HD 152233 is known as an O6 III(f) star (Walborn 1972; Levato & Malaroda 1980) that displays small RV shifts (e.g. Struve 1944). Based on data from the literature along with four additional observations, GM01 proposed a short period of 4.15 d. According to their Table 2, they measured the same RV in two spectra separated by one day. Consequently, they adopted an extremely large eccentricity $e = 0.57$, thus making HD 152233 a potential cornerstone for the study of the dynamical evolution of O-type binaries.

In 2004 May, we observed the system twice a night for six consecutive nights, thus well sampling the proposed 4.15 d period. However, we definitely ruled the latter out as we only detected a slow trend in the system RVs (Fig. 4). The current data set points to a period of several hundred days but awaits further constraints. Our 2003 May data revealed for the first time the signature of the secondary component in the blue wing of the He I and He II lines (Fig. 5). Despite the fact that the lines are only marginally disentangled, we estimated individual spectral types of O5.5 and O7.5 for the two components. The He II λ 4686 line displays a variable P Cygni profile. Although the current data set does not allow us to separate the relative contributions of the two components to the He II λ 4686 profile, its EW is compatible with both stars being giants. Finally, we also detected N III lines that are usually not present in a typical O5.5 III spectrum. These lines are moving in the opposite direction compared to the primary lines. Clearly this is also the signature of the companion, a less evolved O star of spectral type O7.5 or later. While more numerous disentangled spectra are needed to better constrain the nature of the secondary, HD 152233 is definitely a long-period O + O binary.

3.2.3 HD 152247

At 11 arcmin north of HD 152248, HD 152247 has clearly suffered from a lack of attention in the previous works. Mostly classified so far as O9.5 III (Houck 1956; Feinstein & Ferrer 1968; Mathys 1988; Penny, Gies & Bagnuolo 1996), the star seems to be constant in the V band (Balona 1983) with a range in the published values smaller than 0.05 mag. Owing to the absence of the star in the usual photometric works on the cluster, we adopted the magnitude of Diplás & Savage (1994): $V = 7.18$. The first RVs were obtained by Struve (1944) who quoted values around -16 km s^{-1} (rms $\sim 10 \text{ km s}^{-1}$). No other measurement was obtained until Raboud (1996) suggested that the

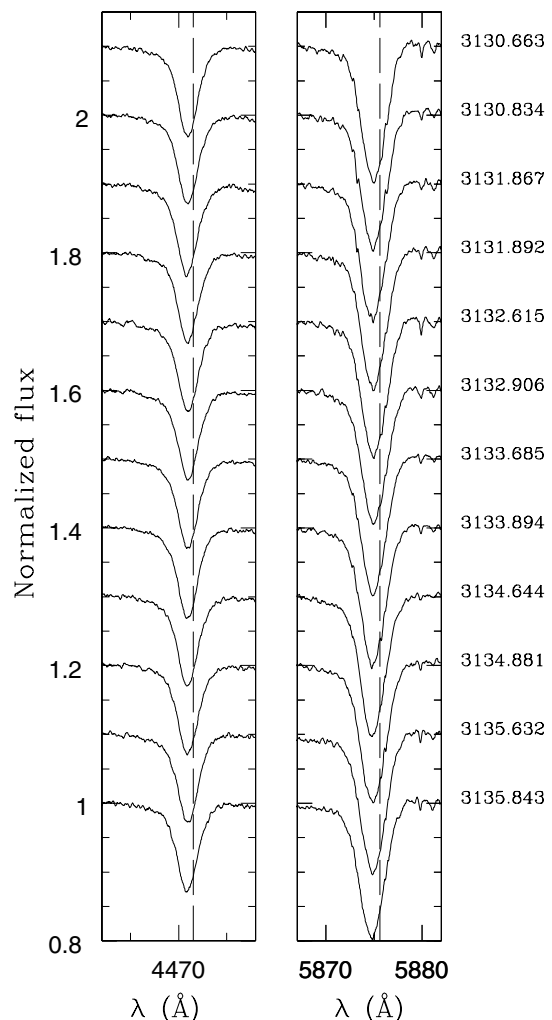


Figure 4. HD 152233: He I λ 4471 and 5876 line profiles as observed during a six-night run in 2004 May. HJD at mid-exposures are quoted at right-hand side in the format HJD -2450000 . The vertical dashed lines represent the rest wavelength. No significant difference in the position of the absorption lines is observed from one spectrum to the other, ruling out the 4.15 d period derived by GM01.

star was displaying RV shifts. He indeed reported five measurements spread over two observing epochs (see the WEBDA data base¹). The first set was acquired over three consecutive nights and indicated values around $+20 (\pm 3) \text{ km s}^{-1}$. The next two measurements were obtained about two years later, again on two consecutive nights, and yielded values close to $-23 (\pm 2) \text{ km s}^{-1}$. More recently, Stickland & Lloyd (2001) reported two additional observations from the *International Ultraviolet Explorer* (IUE) obtained about 10 yr before Raboud (1996) and indicating $\text{RV} \sim -39 (\pm 1) \text{ km s}^{-1}$. Though the star clearly showed RV variations, the time-scale over which these occur remained very poorly constrained.

In our data, clear RV shifts are noticeable from year to year (Figs 6 and 7). The two extreme RV values in our set are approximately -40 (1999, 2004) and $+20 \text{ km s}^{-1}$ (2006). In 2004 May, we obtained six spectra over six consecutive nights but the HD 152247 spectrum remained almost unchanged. Similarly no significant shift was observed between the 2002 March and April data. In 2006 April, we

¹ <http://www.univie.ac.at/webda>.

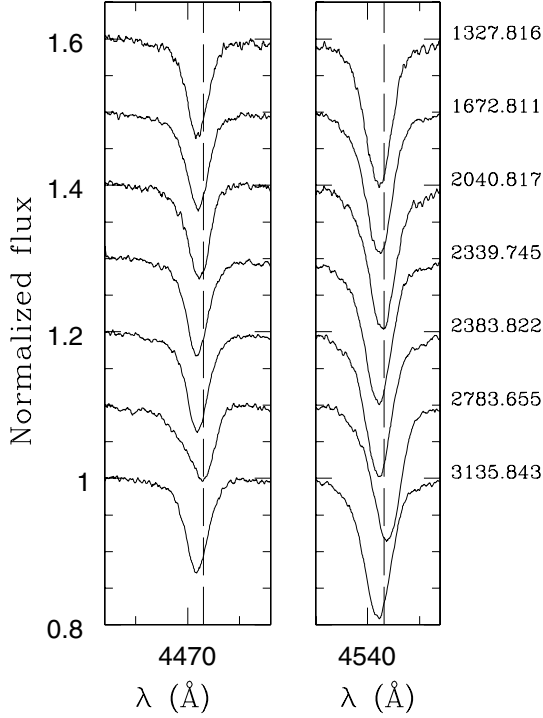


Figure 5. HD 152233: He I λ 4471 and He II λ 4542 line profiles as observed during different observing runs from 1999 to 2004. Clear shifts are seen and the profile asymmetry in 2003 May (HJD \sim 2452784) suggests that the secondary is a late O-type star. The layout of the figure is similar to the one of Fig. 4.

unambiguously detected for the first time the signature of the secondary star. Values for $\log W'$ and $\log W''$ point towards the primary being an O9 III star. In addition, the secondary displays a clear He II λ 4686 line in absorption and is thus an O-type star as well. Because of the blending with neighbouring primary lines, the disentangling of the secondary classification lines is difficult. To correct for the primary line, we subtracted a spectrum where the two components were deblended from one where they were blended, taking into account the measured Doppler shift. In principle, the primary signature should be removed, leaving a positive and negative im-

age of the secondary spectrum shifted from one another. Using this rough method, we estimate that the secondary is probably an O9.7 dwarf.

Again, more disentangled spectra are needed to confirm the classification of the secondary and to constrain the orbital period, which is probably of the order of years. Still, the present results indicate that HD 152247 is an additional O + O binary in NGC 6231.

3.2.4 HD 152314

At 4.2 arcmin east–north–east of the cluster core, HD 152314 is a late O-type object. With $V = 7.92\text{--}8.12$, Feinstein & Ferrer (1968) reported that the star displays photometric variability. RCB97 further found long-term variability on a time-scale of ~ 18 yr. These variations display different amplitudes in the different bands of the Geneva system: the star is becoming bluer when it brightens. RCB97 also suggested an additional, shorter time-scale variability of the order of 1.5 months. RV measurements by Struve (1944), PHYB90 and LM83 do not present any particular variation and the latter authors reported the star as RV constant. More recently, GM01 obtained three additional spectra: two separated by 4 d, another acquired about two years later. Though with some uncertainty on the RV measurements, they reported to have detected the signature of a blueshifted secondary component on the first spectrum of their series, thus suggesting variability on a time-scale of days. The spectral types quoted in the literature are O8.5 III (Levato & Malaroda 1980), O9 III (Schild, Hiltner & Sanduleak 1969; PHYB90) or O9 V (Morgan, González & González 1953a). The remark by RCB97 that the object’s colour is changing with time could also indicate a slight change in its spectral type.

We have acquired a few FEROS spectra of HD 152314 since 2000 May. In 2004 May, we acquired nine spectra over a six-night run. The night-to-night variability is very limited but we observed significant changes from one year to the other (Figs 7 and 8). In 2003 May, we detected the presence of a secondary companion in most of the He I and Balmer lines. The H α profile presents mixed absorption and emission and evolves from an inverse P Cygni profile to a normal P Cygni through the years, a behaviour that could be compatible with an absorption component moving on top of a slightly broader emission. The spectral type changes from O9 to O8.5 between 2000 and 2004, but this could be due to an effect of line blending. The

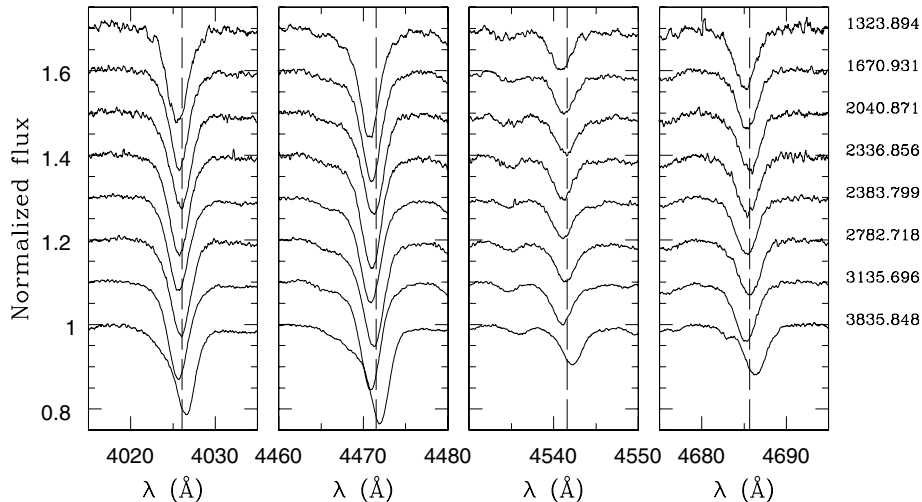


Figure 6. HD 152247: He I $\lambda\lambda$ 4026, 4471 and He II $\lambda\lambda$ 4542, 4686 line profiles as observed during different runs from 1999 to 2006. The spectral signature of the companion is clearly seen in the 2006 spectrum (at HJD \sim 2453836). The layout of the figure is similar to the one of Fig. 4.

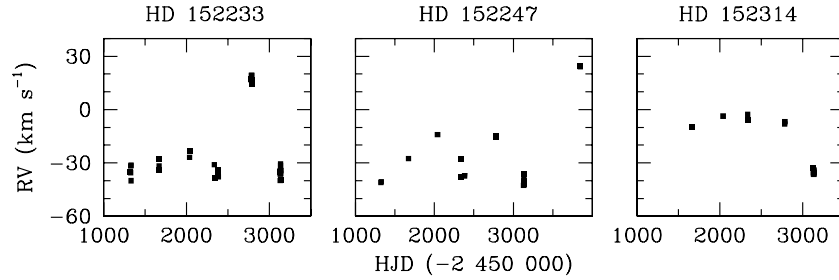


Figure 7. RV variations of the three long-period binaries with ill-constrained periods: HD 152233 (He I λ 5876), HD 152247 (He I λ 5876) and HD 152314 (He II λ 4686).

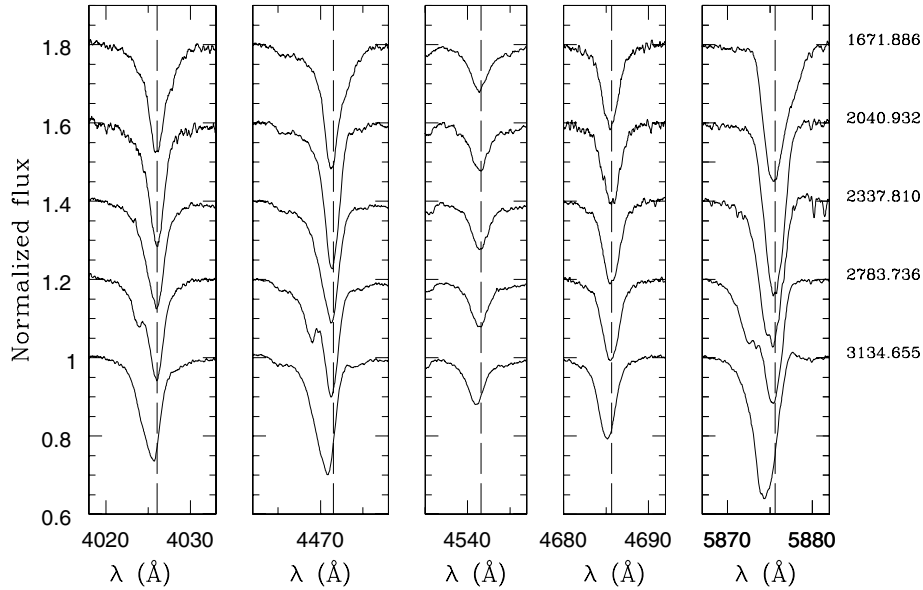


Figure 8. HD 152314: He I $\lambda\lambda$ 4026, 4471, He II $\lambda\lambda$ 4542, 4686 and He I λ 5876 lines acquired during five different observing runs. The spectral signature of the companion is clearly seen in the 2003 May spectrum (at HJD \sim 2452784). The layout of the figure is similar to the one of Fig. 4.

best spectral type estimate is probably obtained in 2003, when the two components were deblended, which indicates an O8.5 III primary. The He II lines seem to belong solely to the primary. The secondary component is thus probably a B-type star. However, its signature remains undetected in the metallic lines, rendering an accurate spectral classification very difficult. Because of the strong secondary signature in the He I lines, its classification could be located around the He I maximum, i.e. at spectral-types B1–B3. This classification remains however uncertain. Finally, with $V = 7.749$ and $B - V = 0.525$, we obtained $M_V = -4.95$ for the system, significantly fainter than a typical O8.5 III star ($M_V^{O8.5III} = -5.32$, Martins, Schaerer & Hillier 2005). This situation is reminiscent of the one observed for other O-type binaries in the cluster. We thus assume that the primary is rather a dwarf and we adopt, as our best classification, O8.5 V + B1–3 V. This object definitively deserves follow-up observations covering time-scales from weeks to years.

3.3 Variable stars

3.3.1 HD 152200

HD 152200 is a late O-type star located about 3.6 arcmin west-south-west of HD 152248. It is quoted as variable by Feinstein & Ferrer (1968), with $V \sim 8.35$ – 8.42 . Photoelectric measurements reported in other works since the 1960s are all in the range 8.41–8.44,

except the measurement from Oja (1986, $V = 8.37$). More recent CCD photometry yielded values between 8.31 (BVF99) and 8.42 (BL95). Regarding the spectral types, Schild et al. (1969) classified HD 152200 as O9.5 III, Houk (1978) as O9 III, whereas Levato & Malaroda (1980) and PHYB90, respectively, preferred O9.5 V(n) and B0 IV classifications. LM83 reported three RV measurements on three consecutive nights, which indicate a velocity change of about 70 km s^{-1} from one night to the other. The Ca K-corrected velocities of PHYB90 show a 30 km s^{-1} range on three measurements spread over 10 d. Finally GM01 claimed to have detected the secondary component signature on two out of their five spectra. The system should apparently have a period of a few days as the lines are reported as blended one night and as separated by $\sim 180 \text{ km s}^{-1}$ the following night.

From 1999 May until 2004 May, we collected 16 FEROS spectra spread over different time-scales. The optical spectrum of HD 152200 is characterized by the Balmer, He I and He II lines. The few metallic lines typical of late O-type objects are also clearly seen. The line profiles are variable (Fig. 9) but no obvious signature of a companion could be found. The observed variations display a peak-to-peak amplitude of 50 km s^{-1} and seem to have a period close to 5 d. The H β line behaviour (Fig. 9) is clearly different from what was reported by GM01. The maximum night-to-night shift is about 30 km s^{-1} (to be compared with the 70 km s^{-1} shift observed by LM83). From our observations, the central value around which

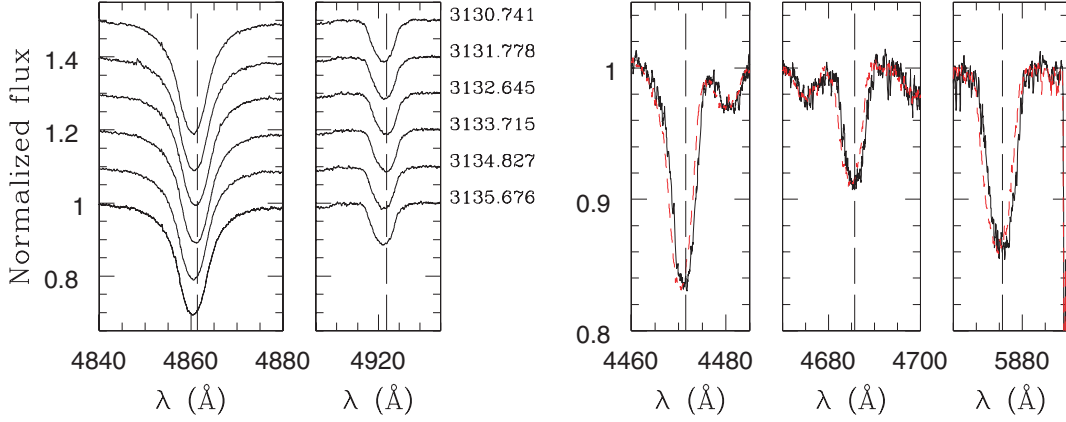


Figure 9. HD 152200: Left-hand panel: Evolution of the H β and He I λ 4921 lines during six consecutive nights in 2004 May. The layout of the figure is similar to the one of Fig. 4. Right-hand panel: He I λ 4471, He II λ 4686 and He I λ 5876 lines obtained in 2000 (HJD = 2 451 669.900, solid line) and 2004 (HJD = 2 453 135.676, dashed line).

the variations occur seems to have shifted by about 10–15 km s^{−1} between the years 2002 and 2004. It could however be an apparent effect resulting from a too sparse sampling of the possible \sim 5-d period. We used the Lafler & Kinman (1965) and the Heck, Manfroid & Mersch (1985) period search techniques and two aliases were found around $P \sim 4.44$ and 5.56 d. However, both period values yield a large scatter of the RV measurements plotted against a hypothetical phase and it seems difficult to interpret the RV variations in terms of a Keplerian motion. Still, the amplitude of the RV variations compared to the ones of the other O stars in the cluster (Fig. 10) pinpoints HD 152200 as a good binary candidate.

The measured EWs correspond to an O9.7 star with spectral type O9.5 at 1σ . Conti’s criterion (W'') clearly indicates a giant class while Mathys’s criterion (W''') rather points towards class V. We computed the absolute visual magnitude to be about $M_V = -4.08$ which is typical of a main-sequence O9.7 star. Though binarity

would provide the most straightforward explanation to the observed RV variations, we have not been able to satisfactorily fit the data, nor have we been able to detect the companion’s signature. More observations are needed to confirm or invalidate the multiplicity status of this object.

3.3.2 HD 152249

HD 152249 is one of the brightest members of the cluster. Its visual magnitude, as quoted since the 1960s, is in the range 6.43–6.51, with the notable exception of Feinstein & Ferrer (1968) who reported the star as variable with $V = 6.34$ –6.50. Quoted spectral types are O9–B0 Ia/b/ab, with the exception of RCB97 who listed O7–O9 V! HD 152249 is adopted by Walborn & Fitzpatrick (1990) as an OC9.5 Iab standard. Several authors indicated RV variations. Neubauer (1930) obtained a Δ RV range of 46 km s^{−1} on 3 plates and classified it as a SB. Struve (1944) and PHYB90, respectively, obtained 15 and 13 measurements on a time-span of 16 and 75 d. Both data sets display a similar range as the one obtained by Neubauer (1930). However, these do not present the smooth variations that could be expected for a binary with a period larger than a couple of days. Later on, Garmany, Conti & Massey (1980) and Levato et al. (1988) obtained additional measurements that do not indicate night-to-night variability but, separated by about 5 yr, they differ by 20 km s^{−1}.

Between 1999 and 2004, we collected 34 spectra. The peak-to-peak dispersion over the 6 yr is 20 km s^{−1} and the night-to-night variability has an amplitude of \sim 10 km s^{−1}. We consider the star to present slight RV changes but clearly, we cannot associate these with a binary nature. The measured EWs unambiguously lead to an O9 I spectral type, thus slightly different from the Walborn & Fitzpatrick (1990) classification. With $V = 6.44$ and $B - V = 0.19$, we obtained $M_V = -6.1$, quite typical of Ib supergiants rather than Iab (Lang 1992). With the presence of the N III λ 4634–4641 lines in weak emission, we finally adopt an O9 Ib (f) classification.

3.3.3 HD 326331 \equiv CPD −41°7744

With $V \sim 7.5$ (SBL98), HD 326331 is an O-type star located at 3 arcmin east of the cluster centre. Together with CPD−41°7744B ($V \sim 10$), it forms a visual pair separated by 7.3 arcsec. If physically related, their revolution period should be over 200 000 yr

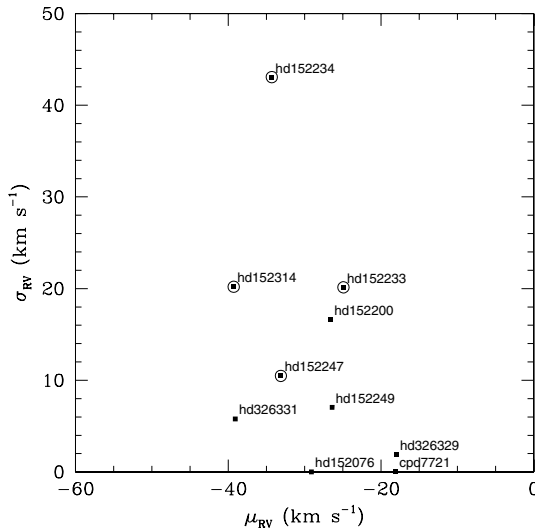


Figure 10. Mean RV (μ_{RV}) and 1σ dispersion (σ_{RV}) for the 10 O-type stars/binaries described in Sections 3.2 and 3.3. Circles indicate the definite binaries in our sample. This graph is based on the He I λ 5876 line measurements only to preserve the homogeneity of the data set and to avoid biases induced by combining different lines for different objects. σ_{RV} is arbitrarily set to 0 for the two objects with only one RV measurement.

(Mason et al. 1998). Quoted spectral types range from O7 III (Levato & Malaroda 1980; LM83) to O9 III (HCB74), but only give the composite classification. The system was reported as photometrically variable by PHC91, and HCB74 mentioned an amplitude of 0.3 mag. If we ignore the value $V = 7.71$ from Feinstein & Ferrer (1968), then all the published photometric data since the 1960s indicate a maximum amplitude of 0.15, with an average value of 7.52 ± 0.08 . RV measurements were obtained by Struve (1944), PHYB90, HCB74 and LM83. The HCB74 data consisted of 13 spectra obtained over seven consecutive nights. Based only on the O II λ 4069 and Si IV λ 4089 lines, they reported smooth velocity variations between $+94$ and -124 km s $^{-1}$ (mean error of 13 km s $^{-1}$) and then up again. They thus suggested that the star is a binary with a period $P \gtrsim 7$ d. They however cautioned that ‘the spectrum is very difficult to measure as the lines are weak’. Finally, using one additional measurement obtained about 7 yr later, LM83 published a first SB1 orbital solution with $P = 6.24208 \pm 0.00015$, $e = 0.12 \pm 0.09$ and $K_1 = 75 \pm 8$ km s $^{-1}$. The obtained residuals (~ 17 km s $^{-1}$) are however very large compared to other orbital solutions published in the same paper.

We have sparsely observed HD 326331 since 1998. We obtained four spectra of the He I λ 4471 region with the CES in 1998 May, which revealed very broad lines (> 10 Å). We then successively acquired FEROS spectra in 1999 May (5), in 2002 April (2) and in 2004 May (6). These were usually separated by one night to cover the proposed 6.4-d orbital period. The spectrum of HD 326331 presents the clear signature of the usual Balmer, He I and He II lines. Both He II λ 4686 and H α profiles show mixed absorption and emission. A faint emission component could also be present in the red wing of He I λ 5876. The lines present a flat bottom and their profiles are therefore clearly not Gaussian (Fig. 11). The broadness of the lines definitely suggests that HD 326331 is a rapid rotator and we used the Fourier transform of the line profile (Gray 2005, and references therein) to estimate a rotation velocity $v \sin(i) = 310$ km s $^{-1}$. Then, assuming that the shape of the lines is fully determined by the rotational broadening, we used a rotation profile with $v \sin(i) = 310$ km s $^{-1}$ to fit the He I λ 4471, 5876 and He II λ 4542 lines. The obtained RVs are reported in Table 3 and show 1σ range of about 3–9 km s $^{-1}$.

Though the peak-to-peak dispersion seen in our measurements is about 20 km s $^{-1}$, we never obtained such highly positive RVs as the ones reported by HCB74. Still, Fig. 11 shows that the spectrum of the star displays obvious profile changes. Though their nature is unclear, it seems difficult to relate them to the presence of a secondary companion and we consider them as intrinsic to the star.

To estimate the spectral type, we measured the EWs of the usual classification lines. For this peculiar object, we integrated the different line profiles rather than adopting the EWs of the fitted profile. Measured values point towards an O8 I star. However, with the He II λ 4686 and H α lines showing mixed absorption and emission, with N III λ 4634–4641 weakly in emission and with clearly delineated He I λ 4388, the observed spectrum is not that of a supergiant. Furthermore, rapid rotation is rather unlikely for a supergiant. We thus prefer the III((f)) classification. With $V = 7.50$ and $B - V = 0.18$, the visual absolute magnitude of the object is about $M_V = -5.2$, which again rules out a supergiant classification. According to Howarth & Prinja (1989) and Humphreys & McElroy (1984), this value is rather typical for giant stars. While determining the nature of the observed line profile variations (LPVs) requires more follow-up, we can however rule out the 6 or 7 d period previously claimed by LM83 and, until proven to be otherwise, we consider the star as single.

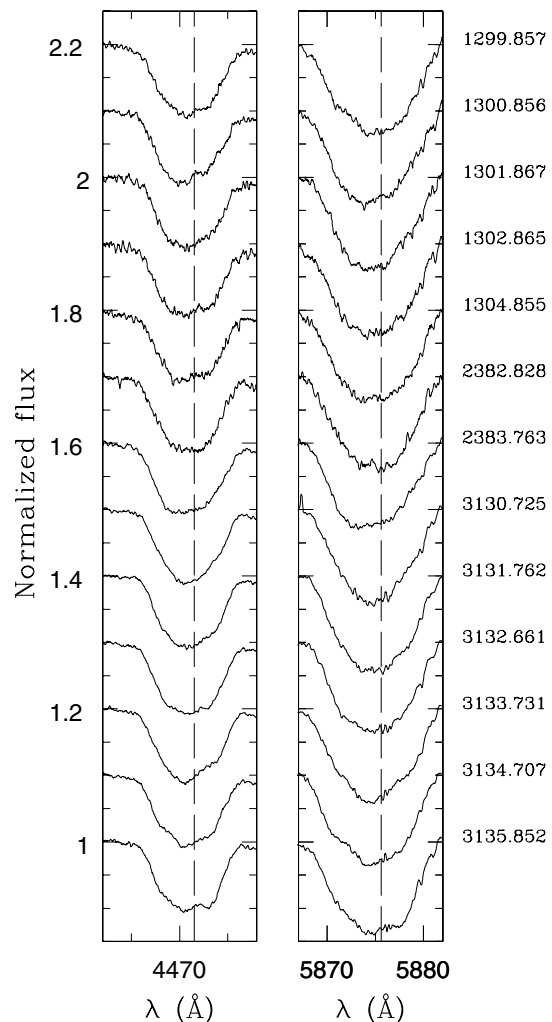


Figure 11. HD 326331: He I λ 4471, 5876 line profiles as observed from 1999 to 2004 on various consecutive nights. The layout of the figure is similar to the one of Fig. 4.

3.4 Presumably single stars

3.4.1 HD 152076

Somewhat offset from the cluster core, HD 152076 had so far received less attention than the other bright stars. Some confusion seems to exist about its magnitude and indeed, cross-identifiers reported in the SIMBAD data base are clearly erroneous. For example, SIMBAD associates HD 152076 with the star Se 309/SBL 350. HD 152076 however lies outside the field of investigation of these two studies (RCB97; SBL98). It is obvious from a comparison with neighbouring objects in DSS images that the $V = 10.85$ mag reported in SIMBAD is wrong. We adopt in the following $V = 8.471$ (Sung, private communication) which is close to previous determinations of $V = 8.5$ (PHYB90), 8.48 (PHC91), 8.47 (Schild et al. 1969), 8.50 (Feinstein & Ferrer 1968), 8.46 (Bok, Bok & Graham 1966) or 8.48 (Heske & Wendker 1984). Quoted spectral types are in the range B0 V (Morgan, González & González 1953a; Morgan, Whitford & Code 1953b) – B0/I III (Schild et al. 1969; Houk 1978). A couple of RV measurements were also performed by Struve (1944), Wilson (1953) and PHYB90 who obtained a Ca K -corrected

RV of about -25 to -30 km s $^{-1}$. Balona (1983) reported this object to be constant in the Johnson B filter on a time-scale of 5 h.

We acquired one snapshot FEROS spectrum of HD 152076 that reveals relatively narrow lines. The He II signature is faint, but clearly seen, and spectral criteria indicate an O9.5 V/III star. With $V = 8.471$ and $B - V = 0.240$, we obtained $M_V = -4.4$, an intermediate value between typical absolute magnitudes of O9.5 dwarfs and giants. HD 152076 is quite offset from the cluster core and thus might not belong to NGC 6231. Instead the star could belong to the Sco OB 1 association, located at the same distance and with a similar age as NGC 6231. Though its luminosity does not agree perfectly with the spectral type deduced from the spectroscopic criteria, HD 152076 is unlikely to be a background object. Because of the narrow lines, suggesting a lower gravity, and the relatively strong metallic spectrum, we opted for an O9.5 III classification. RV measurements performed on the classification lines plus Mg II λ 4481 give $\overline{RV} = -30.7 \pm 2.7$ km s $^{-1}$, in good agreement with previous measurements. We thus consider HD 152076 to most probably be a single star, though it is obviously difficult to discard the possibility of a very long-period binary.

3.4.2 HD 326329 \equiv CPD $-41^\circ 7735$

HD 326329 is located in the core of the cluster. With $V \sim 8.8$, it is relatively bright and has thus been observed for a long time. Derived spectral classifications oscillate between O9 and B0 and agree on the main-sequence luminosity class. A relatively large scatter in the reported visual magnitudes led some authors to consider this object as variable. Focusing on CCD data published since the 1990s, we find V in the range 8.71 (RCB97) – 8.81 (BL95). LM83 and PHYB90, respectively, obtained 3 and 2 spectra of HD 326329 and found consistent RVs (respectively $\overline{RV} = -30(\pm 2)$ and $-30(\pm 5)$ km s $^{-1}$). GM01 obtained three additional spectra spread over 6 d. They derived RVs from -34 to -60 km s $^{-1}$, thus largely scattered and quite different from the cluster systemic velocity, but did not comment on these facts.

We obtained two FEROS spectra in 2000 May and six additional spectra in 2004 May. Within our data set, HD 326329 does not present any significant RV change. For example, we obtained $\overline{RV} = -20.3 \pm 1.5$ km s $^{-1}$ for the He I λ 4388 line, $\overline{RV} = -18.0 \pm 1.9$ km s $^{-1}$ for the He I λ 5876 line and $\overline{RV} = -16.5 \pm 2.2$ km s $^{-1}$ for the He I λ 7065 line. The spectrum of HD 326329 displays the clear signature of an O9.5 V star, with the O9 type at 1σ . Finally, with $V = 8.76$ and $B - V = 0.17$, we obtained $M_V = -3.8$, which is slightly too faint for an O9.5 V star at the cluster distance.

Though no significant RV shift is found from our data alone, we note that the average RVs reported by different authors are only marginally compatible with our data. This could suggest a long-period modulation but only a long-term monitoring of this object could bring an answer to this question.

3.4.3 CPD $-41^\circ 7721$

Together with CPD $-41^\circ 7721s$ ($V = 8.90$), CPD $-41^\circ 7721$ ($V = 8.72$) is a visual double star with components separated by ~ 5.8 arcsec and corresponding to SBL 350 and 351 or BVF 12 and 27. Two spectra were obtained by PHYB90 indicating $RV = -23$ and -28 km s $^{-1}$ (mean error ~ 10 km s $^{-1}$). GM01 also acquired two spectra of the bright component and quoted $RV = -26.8$ and -33.0 km s $^{-1}$. They assigned it a spectral type O9.5 V.

In 2004 May, we obtained one FEROS spectrum of CPD $-41^\circ 7721$ and another of CPD $-41^\circ 7721s$. Each of the two spectra shows a single spectral signature. Consequently, we consider the two stars as apparently single. CPD $-41^\circ 7721$ is an O9 V star with an average RV of -25.5 km s $^{-1}$, although we observed a large scatter (from -36 to -13 km s $^{-1}$) according to the various lines measured. With no He II λ 4542 line and a faint He II λ 4686 line, CPD $-41^\circ 7721s$ is clearly an early B-type star. The strengths of the Si III λ 4552 and Si IV λ 4089 lines are very similar. Comparing with the spectral atlas of Walborn & Fitzpatrick (1990), we finally adopt a B1 V class. With $V = 8.709$ (respectively $V_s = 9.892$) and $(B - V) = 0.168$ [respectively $(B - V)_s = 0.178]$, the visual magnitude of CPD $-41^\circ 7721$ (respectively CPD $-41^\circ 7721s$) is about $M_V = -5.2$ (respectively $M_{V,s} = -2.6$). Both stars are a few tenths of a magnitude too faint if located in the cluster core. Alternatively, slightly later spectral types would yield a much better agreement.

4 DISCUSSION

4.1 Minimum SB fraction

As mentioned earlier, and taking into account WR 79, 16 objects containing at least one O-type star are located within 15 arcmin from the cluster centre. As shown in Figs 1 and 12, these stars are unevenly spread across the field of view. Most of the objects are located in the vicinity of the cluster centre: 10 of them lie within one cluster core radius ($d_c = 3.1$ arcmin), while 13 of them are to be found within $1.5 d_c$. Among these 16 objects, six are close SB2 binaries with periods below 10 d, four are longer period systems, three stars display LPVs and three stars show constant RV and constant line profile.

Given the evidence presented in Section 3, no doubt remains about the multiple nature of the six short-period and of the four longer period systems, though the orbital properties of the latter ones await tighter constraints. This yields a firm lower limit on the fraction of binaries in NGC 6231 of $f_{\min} \sim 0.63$.

In Section 3, we further noted that other objects were presenting hints of binarity, among which HD 152200 and HD 326329 are probably the two best candidates. If the multiplicity of these objects is confirmed, this would significantly increase the binary fraction compared to the lower limit mentioned above. Yet we consider that, so far, there is not enough observational evidence to support such an assertion.

4.2 Statistical significance of the results

While the previous paragraph established that in NGC 6231 the true O-type binary fraction f is located between 0.63 and 1.00, the present results have implications beyond the sole case of NGC 6231 and allow us to put some interesting constraints on the parameters of the underlying distribution of single versus binary stars.

Let us adopt a binomial distribution $B(n, p)$, with n the number of trials and p the probability of realization, to describe the current experiment (i.e. counting multiple stars in a sample of n objects). Given the current realization of the experiment (10 multiple stars among 16 objects), one can compute that the probability of realization p of the parent distribution has to be larger (at the 0.01 significance level) than 0.37. Assuming that some binaries have remained undetected despite our efforts, the parent distribution parameter p would be drawn towards larger values, so that the lower limit $p > 0.37$ still holds at the 1 per cent significance level (or better).

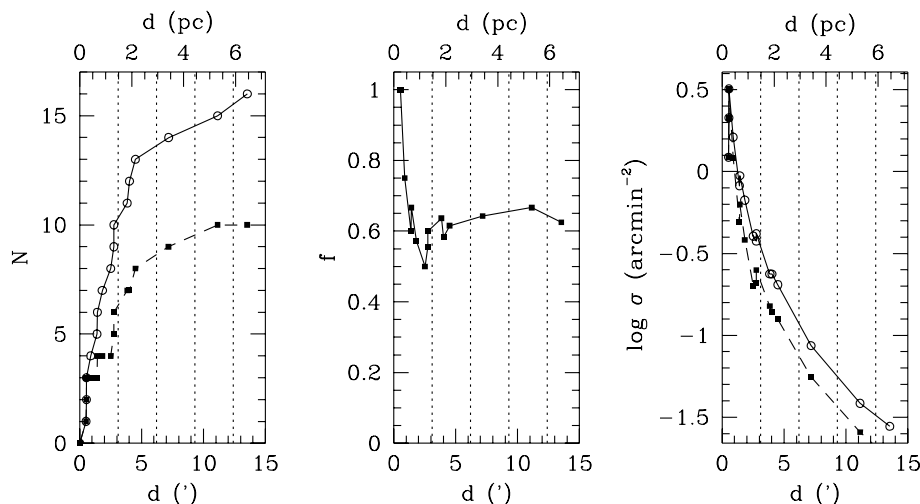


Figure 12. Left-hand panel: Cumulative distribution of the number of O-type objects (solid line and open symbols) and O-type binaries (dashed line and filled symbols) as a function of the distance d from the cluster geometric centre. Middle panel: Evolution of the binary fraction with d . Right-hand panel: Integrated O-star number density ($\sigma = N/\pi d^2$) versus d . Symbols and lines have the same meanings as in the left-hand panel. In all three panels, vertical dotted lines indicate multiples of the core radius $d_c = 3.1 \text{ arcmin} \equiv 1.5 \text{ pc}$.

4.3 Orbital parameters

The orbital parameters that we have derived for the short-period binaries in NGC 6231 (see Table 4) also reveal a significantly different picture than that previously accepted. In particular, while GM01 proposed eccentricities up to 0.6 for the short-period binaries, we discard these values as resulting either from erroneous Julian Dates that pull the eccentricities towards larger values (see e.g. Sana et al. 2003) or from ill-constrained periods biasing the orbital fit. From our results, none of the short-period binary stars has an eccentricity larger than 0.3. As a consequence, the NGC 6231 binaries are now in line with the period–eccentricity distribution of other O-type binary objects (Fig. 13). This has significant implications on the dynamical evolution of the O-type stars as no other binaries with a high eccentricity and a very short period are known so far.

We also note that the short-period systems are significantly more abundant than longer period systems, even compared to Öpik’s law which states that the distribution of the periods (or equivalently, given Kepler’s third law, of the separations) should be flat in the logarithmic space. Indeed, this would translate itself into a linear dependence of the cumulative distribution of the systems, expressed versus the logarithm of the period while Fig. 14 shows that, in NGC 6231, this is not the case. Even if all the non-binaries in the cluster were actually undetected long-period binaries, this fact would remain, so that observational biases cannot be invoked. It is however difficult to decide whether this is a signature of the formation process or of the early evolution history.

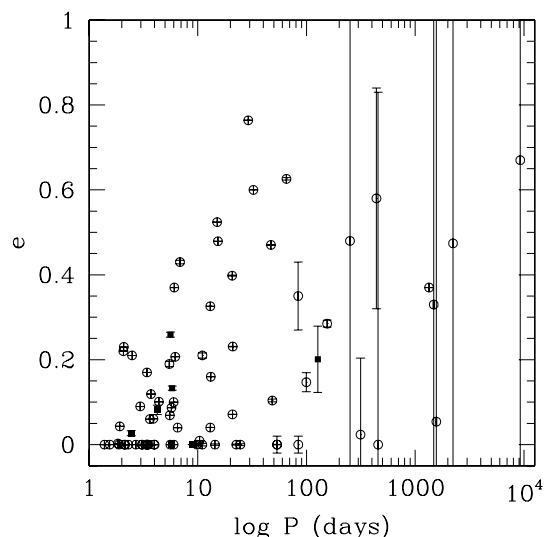


Figure 13. Period–eccentricity distribution for the O-type SB systems listed in the 9th Spectroscopic Binary Catalogue (Pourbaix et al. 2004). Filled symbols indicate the location of the NGC 6231 systems.

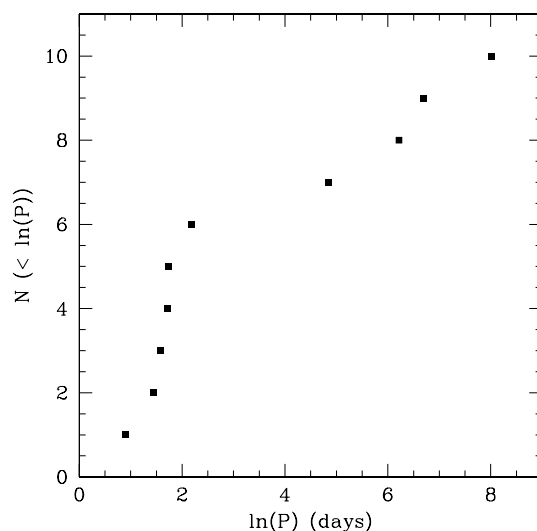


Figure 14. Cumulative number of binary systems, in NGC 6231, as a function of the natural logarithm of the orbital period. Period values above $\ln(P) = 4$ are very preliminary, though the order of magnitude should be correct.

4.4 Mass ratios and companion initial mass function

Not only is the present study based on a complete and homogeneous population of O-type stars, but we emphasize that the signature of all the secondary companions could be unveiled in the detected binaries, yielding an unprecedented view of the binary population parameters. As a matter of fact, all the 10 detected O-type binaries have an OB companion, suggesting luminosity ratios (L_1/L_2) between 1 and 10, and mass ratios (m_1/m_2) between 1 and 3.

Of course the present study is biased towards the detection of relatively massive companions. None the less, taking advantage of the completeness of the population, one can already make the following strong statement. Even if the six remaining presumably single stars are undetected binaries (low-mass or faint companions, pole-on view, etc.), a minimum of two thirds of the companions have a mass above $5 M_{\odot}$. Even considering the possibility of hierarchical multiple systems, the present data set definitely rules out the possibility that the companions in NGC 6231 are randomly drawn from a Salpeter initial mass function (IMF). Indeed, if this were the case, one would expect, for each O + O system, to encounter 9, 13, 19, 22, over 100 and a few hundreds of O-type binaries with a companion of spectral type B, A, F, G, K and M, respectively (Weidner & Kroupa 2008). Considering that, in the present work, one would probably detect O and B companions only, and assuming a 100 per cent binary fraction, a rule of thumb would predict a binary detection rate of 2 per cent only, thus about 0.3 binary given the 16-star sample. Despite the limited size of the sample, the null hypothesis that the companions of an O star are randomly drawn from a Salpeter IMF can be rejected at the 5σ level.²

4.5 Visual companions

The speckle interferometric campaign of Mason et al. (1998) included the brightest objects ($V < 8$) of the cluster and revealed that HD 152233, HD 152234, HD 152248 and, possibly, HD 152249³ have one or several visual companions with a subarcsec separation. Beside these results, direct imaging indicates that CPD $-41^{\circ}7721$ s is located at 5.8 arcsec from CPD $-41^{\circ}7721$, that HD 326329 has a visual companion at 7.3 arcsec and that HD 152076 is not distant by more than 8 arcsec from two other stars. Only HD 152200 remains seemingly alone in a 20 arcsec radius. So far, however, it is almost impossible to state whether these visual pairs are physically linked, or arise by line-of-sight coincidence in such a crowded field.

Using only stars brighter than $V = 17$, one can estimate a density of about 10 stars arcmin⁻² at the cluster centre and about half this value at $1.5d_c$ (Sana et al. 2006b). Rough statistics thus suggest that companions separated by less than 1 and 2 arcsec, respectively (according to whether they are located in the very core or in the outer part of the cluster) are unlikely to arise by chance and are thus likely bound (at the 0.01 significance level). According to this simplistic criterion, only HD 152234, HD 152248 and, possibly, HD 152249 have a physical faint companion with putative revolution periods between 150 and 4900 yr (Mason et al. 1998). If verified, this would indicate that at least one third of the SB systems are hierarchical triple systems, yielding a number of companions per massive star close to 0.8. Such a value remains still far below the 1.4 companion

fraction derived by Preibisch et al. (2001) for the O- and B-type stars in the Orion nebula cluster. As a matter of comparison, either a significant fraction of close and unresolved companions, with a physical separation roughly in the range 2–200 au, are still missing, or one would need to consider all the known visual companions up to 10 arcsec to reach a similar rate for NGC 6231.

4.6 Physical constraints for massive star formation

Because of its spectroscopic approach, the present study is clearly biased towards the detection of SB systems with an OB star companion and only provides a lower limit on the true binary fraction. Even considering the work of Mason et al. (1998), about two orders of magnitude in semimajor axis (i.e. between ~ 2 and 200 au) are still not sampled. Investigations of this range would require 10 m s⁻¹ RV accuracy or milliarcsec spatial resolution, both of which, as far as O-type stars are concerned, challenge the current instrumentation limits. Still the present study provides strong constraints for massive star formation.

(i) At least 60 per cent of the O-type objects in NGC 6231 are SB systems. Over 70 per cent of any O-type star in the cluster are found to belong to an O + O or an O + B system.

(ii) If the properties of the O-star population in NGC 6231 are representative of the O-star population in general, the expected binary fraction of the parent distribution should, at the 0.01 significance level, be larger than 0.37.

(iii) Concerning the 10 SB binaries in our sample, half of them have an O-type companion, the other half having a B0–3 companion. Therefore, in all the detected SB binaries in the present sample, the luminosity ratio is about or less than 10 to 1 while the mass ratio is about or less than 3 to 1.

(iv) Even in the extreme case of a 100 per cent binary content, it is very unlikely that the companion of an O-type star would be randomly drawn from a standard IMF.

(v) As a corollary, the previous statement shows that the massive star formation and/or early evolution tend to produce a large number of double objects with components having masses of the same order of magnitude.

(vi) 60 per cent of the detected SB systems (thus about one third of the O-type objects) are tight binaries with periods between 2.4 and 9 d, and with zero or small eccentricities. Compared to Öpik's law, short-period systems are overabundant, even in the extreme case of $f = 1.0$.

(vii) No significant difference in the spatial distribution of the binary fraction can be found across the cluster (Fig. 12).

5 CONCLUSIONS

Based on a set of high-resolution high S/N spectra of the O-type objects in NGC 6231, covering various time-scales from a few hours to several years, we have revised their physical and orbital status, paying particular attention to their possible multiplicity. The present fraction of binaries in NGC 6231 (around 63 per cent) is significantly reduced compared to the value of 79 per cent obtained by GM01.

We note that the revision of the binary fraction in NGC 6231 puts the cluster in a less extreme position compared to other rich (in terms of the number of O-type stars) open clusters. Considering also that De Becker et al. (2006) could not reproduce the high binary fraction ($f \sim 0.80$) found by GM01 for the cluster IC 1805 either, the anticorrelation proposed by GM01 between the cluster density and its massive star binary fraction remains to be confirmed.

² We note that using a standard Kroupa IMF instead of a Salpeter IMF does not significantly change the present result.

³ Mason et al. suggested that HD 152249 could have a binary companion at a separation of 0.06 arcsec, but they emphasized that this result needs to be confirmed.

While detailed studies of other open clusters are needed, the present approach already offers the possibility to quantitatively test the null hypothesis that the O-type SB populations of different clusters are drawn from the same distribution. Indeed, the rejection of this hypothesis is a pre-requisite to the suggested link between the binary fraction and the cluster properties.

Beyond the binary fraction, we also conclude that, in NGC 6231, the massive stars are not randomly paired from a standard underlying IMF. Instead, there is a strong bias towards the formation of O + OB systems. Among the latter, about half of them are close binaries with a period of a few days. Finally, none of the short-period binaries has an eccentricity larger than 0.3. Compared to the periods and eccentricities found by GM01, this has strong implications on the dynamical evolution of such systems.

The present results outline the limitations of previous estimates of the properties of the O-type population in young open clusters. It also emphasizes the need for extensive studies to accurately constrain, among other properties, the binary fraction of various stellar populations and, particularly, of early-type stars whose formation and evolution are still not firmly understood.

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SUPPLEMENTARY MATERIAL

The following supplementary material is available for this article:

Table 3. Journal of the spectroscopic observations of the NGC 6231 O-type stars studied in the present paper. The two header lines indicate the considered spectral lines and the adopted rest wavelength (in Å). The first column gives the Heliocentric Julian Date at mid-exposure. The following columns provide the heliocentric RVs (expressed in km s⁻¹) using various spectral lines. The last two columns provide the mean and 1σ dispersion computed, for a given date, over the quoted lines. Whenever appropriate, the mean and 1σ dispersion for individual lines are also given at the bottom of each subtable. Table 3 is also available in electronic form at the

CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via VizieR (<http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/MNRAS>). References for the instrumental set-up can be found at the bottom of the table.

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